# Inflation, modulation and baryogenesis with warm directions

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## Abstract

There are many flat directions in SUSY models, which may dissipate their energy and source the radiation background during inflation. However, the only possibility that has been studied in this direction is warm inflation, which uses "warm" (or "dissipative" if we consider more modest situation) direction as the inflaton. In this talk we discuss other significant possibilities of such directions which are dissipative and may or may not be "warm". Affleck-Dine (AD) mechanism and other cosmological scenarios are discussed in the light of "dissipative field", instead of using the conventional light field with mass protection. We sometimes consider Morikawa-Sasaki coefficient for the non-thermal background, which is important because the dissipation calculated for a naive thermal background with $T \to 0$ is not enough to discuss the dissipation with the non-thermal background. (This is a small extended version of the proceedings for the JGRG19.)

## 1 Dissipative directions for particle cosmology

Even in a non-thermal background, dissipation is generic for realistic field motion $\dot{\phi} \neq 0$ that leads to a coherent excitation of a heavy intermediate field $\chi$ that decays into light fermions $\psi_d$. Here we consider a typical interaction given by

$$\mathcal{L}_{int} = -\frac{1}{2}g^2\phi^2\chi^2 - h\chi\bar{\psi}\psi, \tag{1}$$
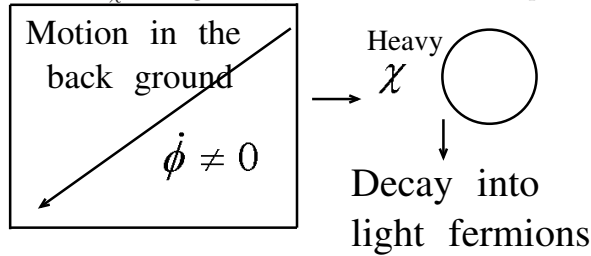
which leads to efficient decay of the intermediate field ($m_\chi \propto \phi$) with the decay rate

$$\Gamma_\chi \simeq \frac{N_\psi}{8\pi}h^2 m_\chi \simeq \frac{N_\psi}{8\pi}h^2 g\phi, \tag{2}$$

where $N_\psi$ is the number of the light fermions. The dissipation coefficient is given by [1–3]

$$\Upsilon \sim N_\chi \frac{\sqrt{2}g^3 N_\psi h^2 \phi}{8^3\pi^2}, \tag{3}$$

which is proportional to $\Gamma_\chi$. In figure 1, we show a schematic picture for the dissipative motion.



Figure 1: "Energy loss" is caused by the correction that has the imaginary part proportional to $\Gamma_\chi$.

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The strength of the "friction" caused by the dissipation is measured by the rate $r_\Upsilon \equiv \frac{\Upsilon}{3H}$. Then the field equation for the dissipative motion is given by

$$\ddot{\phi} + 3H(1 + r_\Upsilon)\dot{\phi} + V_\phi = 0, \tag{4}$$

where the subscript denotes the derivative with respect to the field. The effective slow-roll parameters are suppressed when $r_\Upsilon$ is large ("strongly dissipating");

$$\epsilon_{eff} = \frac{\epsilon}{(1 + r_\Upsilon)^2}, \qquad \eta_{eff} = \frac{\eta}{(1 + r_\Upsilon)^2}. \tag{5}$$

Our claim is very simple. **Dissipative motion is a generic phenomenon, which must be considered not only for the specific inflation model but also for other generic cosmological scenarios.** A **modest** assumption is that the background is **not** thermal, because "warm" background is not essential for the dissipative motion. Of course dissipation may be more significant when the background is thermal, but the required conditions for the thermalization are sometimes very severe. We thus consider non-thermal background during inflation because thermal conditions may spoil the generality of the dissipative scenario. On the other hand, thermal background is natural after reheating. We thus consider thermal background for the field motion after reheating. Assuming a thermal background, $\Upsilon$ can be given by

$$\Upsilon \propto \frac{T^n}{\phi^{n-1}}, \tag{6}$$

where $n = 1$ for high-temperature SUSY and $m = 3$ for low-temperature SUSY.

## 1.1   Natural dissipation in SUSY hybrid inflation

The first example[4] is SUSY hybrid inflation, for which we will argue that the conventional interaction $\mathcal{L}_I \sim -\frac{1}{2}g^2\phi^2\chi^2$ between the inflaton $\phi$ and the trigger field $\chi$ may cause significant dissipation that leads to slow-roll inflation. Namely, $O(H)$ correction from the supergravity may not spoil slow-roll in SUSY hybrid inflation.

The key in this scenario is the gravitational decay $\chi \to 2\psi_{3/2}$ of the intermediate (trigger) field, which leads to an inevitable decay rate

$$\Gamma_{\chi \to 2\psi_{3/2}} \simeq \frac{m_\chi^3}{M_p^2} \sim \frac{g^3\phi^3}{M_p^2}, \tag{7}$$

which is larger than the Hubble parameter $H$ when $\phi > (HM_p^2)^{1/3}/g$. The dissipation coefficient of the inflaton mediated by the heavy trigger field $\chi$ is

$$\Upsilon \sim 10^{-2}\left(\frac{m_\chi}{M_p}\right)^2\phi, \tag{8}$$

which gives the minimal value of $\Upsilon$ caused by the least channel of the gravitational decay. Surprisingly, $r_\Upsilon \gg 1$ is generic for the chaotic initial condition $\phi_{ini} \sim M_p$. See Fig.2.

## 1.2   Dissipative Affleck-Dine field

Considering typical situation for the dissipative motion of the AD field, it is not appropriate to disregard thermal background $T \neq 0$. However, **in contrast to warm inflation** [5, 6], the thermal background is not always due to the dissipation caused by the field motion. Namely, the dissipation coefficient $\Upsilon(\phi, T)$ of the AD field may depend on the environment, temperature of the Universe, which depends on cosmological events other than the Affleck-Dine baryogenesis. Typically, MSSM directions couple to heavy directions that can decay into light fermions. Therefore, non-thermal dissipation would be significant at large distance, and thermal dissipation may be significant during a period depending on the field interaction and the temperature of the Universe. In any case, it is very important to consider dissipation of the AD field before the AD baryogenesis. If the dissipation is large enough to ensure the slow-roll, the AD-field is "trapped" at $\phi_{AD} \neq 0$. **The situation is in contrast with the conventional**
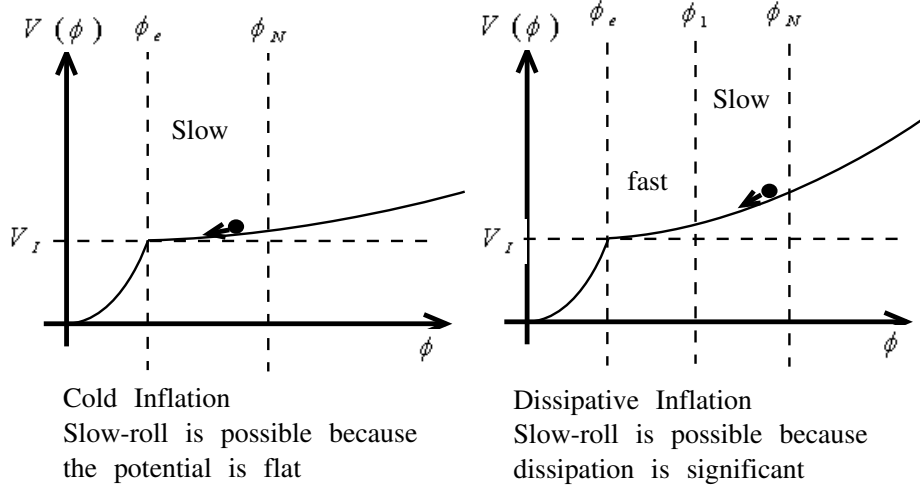
Figure 2: Left : Conventional cold inflation with $m_\phi \ll H$. Right : Gravitational decay of the trigger field causes significant dissipation and slow-roll for $\phi_1 < \phi$ even if $m_\phi \geq H$.

**scenario, in which the "flip" of the potential is responsible for** $\phi_{AD} \neq 0$**.** If the AD field is trapped due to dissipation, the time when oscillation begins is not determined by the usual condition $m_\phi \sim H$.

The situation related to dissipation of the AD field can be summarized as follows.

1) The time when oscillation starts may be different from the conventional (non-dissipating) scenario.

2) The amplitude of the AD-field oscillation may be different.

These differences are expected to lead to crucial discrepancies in the results.

## 1.3   Dissipation before preheating

Above in section 1.1, we considered hybrid inflation in which the typical interaction (inflaton-trigger field interaction) leads to inevitable dissipation. A similar argument may apply to preheating scenario [7–9] in which the typical interaction (oscillating field-preheat field interaction) may lead to significant dissipation and slow-roll before the oscillation. Here we consider "instant preheating" scenario for simplicity, in which instant decay after preheating is assumed. Significant dissipation before the onset of oscillation typically leads to a **delay of the oscillation**. To show explicitly the dissipative effect, we consider a potential with a mass

$$V(\phi) = \frac{1}{2}m^2\phi^2, \tag{9}$$

and the dissipation based on the non-thermal background. The interaction with the preheat field is given by

$$\mathcal{L}_{int} \simeq \frac{g_{PR}^2}{2}\phi^2\chi^2, \tag{10}$$

where **preheat field** $\chi$ plays the role of the **intermediate** field for the dissipation. The decay into light fermions, which is needed for the preheating scenario followed by the instant decay, is induced by the term

$$\mathcal{L}_{\psi\chi} = h\chi\bar{\psi}\psi. \tag{11}$$

Obviously, for $g \sim h \sim O(1)$, the dissipative process $\phi \to \chi \to \psi$ is efficient for the model of instant preheating. In fact, based on the non-thermal dissipation, it is very easy to show the slow-roll conditions that delays the preheating and reduces the amplitude of the oscillation. The dissipation coefficient is

$$\Upsilon \simeq 10^{-2}g_{PR}^2h^2m_\varphi \simeq 10^{-2}g_{PR}^3h^2\phi. \tag{12}$$

Then the effective slow-roll conditions are

$$\epsilon_w \quad \simeq \quad M_p^2 \left( \frac{m^2 \phi_I}{V} \right)^2 \frac{1}{(1+r)^2} \sim \left( \frac{m}{10^{-2} \times \phi_I} \frac{1}{g_{PR}^3 h^2} \right)^2 < 1 \qquad (13)$$

$$\eta_w \quad \simeq \quad \frac{m^2}{H^2} \frac{1}{(1+r)^2} \sim \frac{m^2}{10^{-4} \times \phi^2} \frac{1}{g_{PR}^6 h^4} < 1, \qquad (14)$$

which lead to a simple slow-roll condition $\phi_I > 10^2 \times m/g_{PR}^3 h^2$, where the field motion is **not** oscillationary but simply slow-rolling. Therefore, the usual requirement for instant preheating followed by the instant decay now leads to a new condition for the model, which **affects the initial condition of the oscillation** that determines the amplitude of the oscillation; dissipation leads to a delay of the end of chaotic inflation. In fact, in conventional scenario of preheating after chaotic inflation, the amplitude was simply assumed that $\phi \sim M_p \gg \phi_I$. In contrast to the usual assumption, typical interaction of the scenario may lead to dissipative motion that may lead to significant slow-roll during $M_p > \phi > \phi_I$.
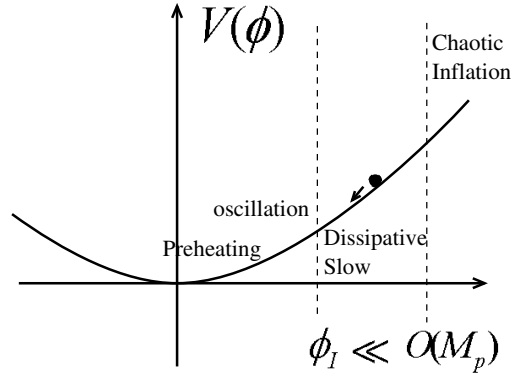


Figure 3: Without dissipation, chaotic inflation is expected to end at $\phi \sim O(M_p)$. However, interactions required for instant preheating suggests that non-thermal dissipation is common in such models and that an error may not be negligible.

## 1.4    Remote inflation (Thermal inflation sourced continuously by dissipation)

If dissipation is generic for many cosmological fields that acquire $O(H)$ mass during inflation, these fields may lead to thermal background during inflation. Note that there are at least **two** significant models in which thermal background is used for inflationary scenario: warm inflation and thermal inflation. In fact, warm inflation is based on the thermal background sourced by the dissipation, while no source mechanism has been considered for thermal inflation. Our idea is based on a naive question: **What happens if radiation in thermal inflation is sourced continuously by (many) cosmological fields that acquire $O(H)$ mass and dissipate their energy during inflation?** Namely, background radiation sourced by dissipation may cause symmetry restoration in a remote sector [10, 11], where thermal inflation occurs. See Fig 4. There are two scenarios depending in which sector the slow-roll condition is broken first. (1) If the end of slow-roll occurs first in the inflaton sector, small thermal inflation will remain in the remote sector. Note that the temperature at this time is still higher than the critical temperature of the thermal inflation sector. (2) If the temperature decreases during inflation and symmetry breaking occurs first in the remote sector, it immediately leads to the end of inflation. See Fig.4.

## 1.5    Conclusions and discussions

In this talk we considered simple examples of cosmological scenarios in which dissipation may change the usual argument based on cold (non-dissipating) scenario. I believe the situation is now obvious suggesting why the dissipation is very important for particle cosmology. The study related to the cosmological dissipation may give us a key to understand the interactions in the particle model in terms of the cosmological observations. In previous studies dissipation has been studied only for the inflaton in the
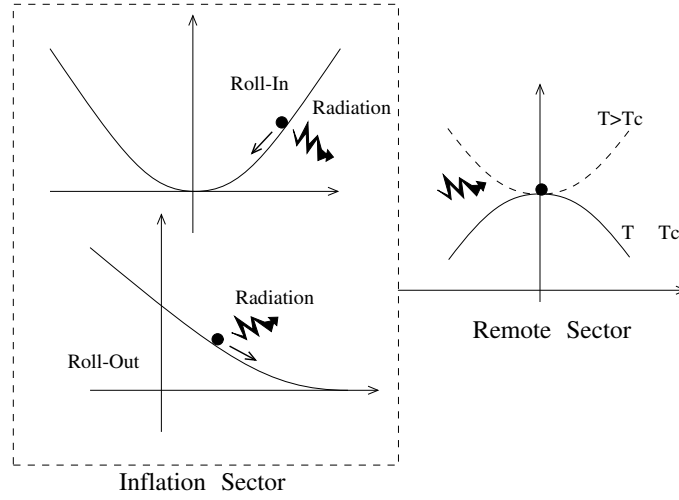
Figure 4: Left : Background radiation during inflation may be sourced by many dissipating fields. Right: Radiation causes symmetry restoration in the remote sector, which leads to thermal inflation sourced by dissipation in the inflation sector. This model looks like a hybrid version of warm inflation.

very early Universe (warm inflation). However, in the light of particle cosmology, dissipation is very important in understanding interactions in the SUSY model [12], GUT or the string theory [13–16].

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